Effect of digester surface area on biogas yield

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Abstract: Poultry manure, cow dung and swine manure were digested in cube-shaped anaerobic digesters of equal volume but different surface areas (*SA*) (5.38, 10.0 and 11.6 dm^2) in a two-factor experiment. The digesters were agitated once a day during the experiment. The results showed that manure type and *SA* only had significant ($p \leq 0.05$) effect on biogas yield (*BY*). Poultry manure had the highest yield, followed by swine manure and cow dung (1.00, 0.59 and 0.11 L kg^{-1} VS fed day^{-1}, respectively). Within the *SA* investigated, *BY* increased as digester *SA* increased (0.27, 0.68 and 0.74 L kg^{-1} VS fed day^{-1} for 5.38, 10.0 and 11.6 dm^2, respectively). The results of the regression analysis showed that a polynomial model presented an ideal situation and best described the relationship between digester diameter to substrate height (*DD/SH*) *ratio* and *BY* through a dome-shaped curve, indicating *DD/SH ratios* at which biogas production would commence, peak and stop.

Keywords: biogas yield, digester surface area, poultry manure, swine manure, cow dung

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1 Introduction

Anaerobic digestion is a biochemical technology for the treatment of organic wastes and the production of biogas, which can be used as a fuel for heating, electricity or vehicle. The process takes place in engineered containment vessels, called bioreactors or digesters, designed to exclude air and promote the growth of methane bacteria. Most studies on anaerobic digestion and optimization of biogas production have focused on feedstock properties, digester temperature, retention time, loading rate, mixing and co-digestion. The basic requirements of an anaerobic digester design are to allow for a continuously high and sustainable organic loading rate, a short hydraulic retention time (to minimize digester volume) and to maximize biogas yield (Ward et al., 2008). Igoni et al. (2008) stated that some factors to be considered when designing digesters, including type and nature of waste, rate of waste generation and local environmental conditions, like the ambient temperature. For effective digestion, digester shape must take into consideration the construction practicalities of both mixing and heat loss (Ward et al., 2008). It is a known fact that the bigger the digester capacity, the more the biogas production, provided decomposition factor levels are kept at optimum. Several studies have focused on the design parameters of digesters for optimum biogas production (Ortolani et al., 1991; Florentino, 2003; Thy et al., 2005; Umaru, 2012; Kaur et al., 2017). Such parameters ranged from digester surface area, diameter and height; positioning of the inlet and outlet pipes; usable and gross volumes of the digester; level of the substrate to volume of biogas needed per day; etc. In addition, some authors have used mathematical models to size digesters for effective biogas production. While results from these studies have advanced knowledge on effective biogas production, the effect of digesters' configuration in terms of the surface area (*SA*) and height on biogas production and the mathematical relationship between digester diameter to digester working height (substrate height) (*DD/SH*) *ratio* and biogas yield (*BY*) are not well understood. This study therefore aimed to fix the digester volume and vary the surface area and height with a view to determining the effect of digester *SA* on biogas production and the optimum *DD/SH ratio* for biogas

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production.

2 Materials and methods

2.1 Materials and analytical methods

The anaerobic digestion experiment was conducted under ambient conditions in a laboratory at the Department of Agricultural and Environmental Engineering of the Obafemi Awolowo University, Ile-Ife, Nigeria. The ambient temperatures during digestion were mesophilic, ranging between 26°C and 34°C. Fresh poultry manure (PM), swine manure (SM) and cow dung (CD) were collected from the University Teaching and Research Farm. Samples were analysed for total solids (*TS*) content (oven drying at 105°C for 24 h); volatile solids (*VS*) content (ashing of TS at 550°C for 5 h); total nitrogen (*TN*) (regular-Kjeldahl method; Bremner, 1996); pH (1:10 w/v sample:water extract, using a digital pH meter). The total carbon (*TC*) content was estimated from the ash content according to the Equation (1) (Mercer and Rose, 1968):

$$TC\ (\%) = [100 - Ash(\%)]/1.8 \tag{1}$$

The initial properties of the manures are presented in Table 1.

Table 1 Initial properties of the manures

MT	Properties (dry weight basis)				
	pH	*VS*, %	*TC*, %	*TN*, %	*C:N ratio*
PM	6.88	66.4	36.9	3.41	10.8
CD	7.13	73.3	40.8	1.88	21.7
SW	6.98	61.2	34.0	2.42	14.0

Note: carbon to nitrogen (*C:N*).

2.2 Experimental set up

The experimental set up comprises of digesters, water tanks and water collectors. The digesters were adapted using cube-shaped 25 L plastic kegs. The kegs were positioned on each of the three sides to give the following surface (dm^2) and height (dm) dimensions: 2.15 × 2.50 and 4.65, 2.15 × 4.65 and 2.5, and 2.50 × 4.65 and 2.15, respectively, resulting in 5.38, 10.0 and 11.6 dm^2 surface areas from the three positions. A drain plug was fitted at the base of each digester for collection of samples for pH analysis. Each digester had a digital thermometer probe fitted to it for temperature measurement. Similarly, the water tanks and water collectors were adapted using 10 L and 5 L rectangular plastic kegs, respectively. Rubber hose was used to connect each digester to the water tank and the water tank to the water collector.

After the moisture content determination, each manure was diluted with clean tap water to 8% *TS*, as recommended by Zennaki et al. (1996), agitated vigorously and poured through a 6 mm plastic mesh to remove gross solids. The digesters were loaded once during the experiment to 70% of their capacities, hence, a working volume of 17.5 L, with substrate height and surface area dimensions of 3.24, 1.75 and 1.50 dm and 5.38, 10.0 and 11.6 dm^2, respectively. The experiment was set up as a 3 × 3 completely randomized block design with manure type (*MT*) and digester *SA* as the variable factors, and each treatment triplicated. The biogas produced was estimated by water displacement method (Archimedes' principle) and measured using a calibrated cylinder (Ogunwande et al., 2013). The digesters were manually agitated once daily to avoid long period settlement of the substrates and ensure uniform distribution of micro-organisms and heat within the substrates. Ambient and substrate temperatures and *BY* were measured daily while substrate pH was measured weekly.

2.3 Statistical analysis

Data collected were subjected to two-way analysis of variance (ANOVA) to compare variations in substrate temperature and substrate pH, and *BY*. Where significance was indicated at $p \leq 0.05$, Duncan's multiple range test was used to separate the means.

The mathematical relationship between *DD/SH ratio* and *BY* was established by regression analysis. The *SA* were assumed to be circular and the respective diameters were estimated and divided by the corresponding substrate heights to give the *DD/SH ratios*. The *BY* obtained from the three *SA* represented yields from the corresponding *DD/SH ratios*. Four mathematical models (logarithmic, power, polynomial and linear) were fitted to the ratio and yield data to obtain equations which were used to predict biogas yields from given *DD/SH ratios*. Both ANOVA and regression analysis were performed using the Statistical Analysis Systems software (SAS, 2002).

3 Results and discussion

The livestock wastes were digested for 49 days. The initial properties were within the range obtained in previous studies (Ogunwande et al., 2008; Bernal et al., 2009; Ogunwande et al., 2013), but the *C:N ratios* of PM and SM were below the range of 20:1-30:1 recommended for effective biodegradation (Rynk et al., 1992). However, the low levels did not have adverse effect on *BY* as the manures still produced more than CD that had *C: N ratio* within the range. The results of the statistical analysis revealed that *MT* and *SA* only had significant ($p \le 0.05$) effect on biogas yield (Table 2).

Table 2 ANOVA table showing the effects of *MT* and *SA* on measured parameters

Parameter	Source	Df	SS	MS	*F*-value	Pr>*F*
Temperature	*MT*	2	3.754	1.877	1.182	0.330
	SA	2	5.599	2.799	1.762	0.200
	*MT*SA*	4	7.285	1.821	1.147	0.367
	Error	18	28.594	1.589		
pH	*MT*	2	0.025	0.013	0.266	0.769
	SA	2	0.016	0.008	0.169	0.846
	*MT*SA*	4	0.066	0.016	0.347	0.843
	Error	18	0.854	0.047		
Biogas	*MT*	2	3.600	1.800	16.789	<0.0001
	SA	2	1.157	0.578	5.394	0.015
	*MT*SA*	4	0.735	0.184	1.714	0.191
	Error	18	1.930	0.107		

Note: $p \le 0.05$ indicates significance. Df, degrees of freedom; SS, sum of squares; MS, mean of squares.

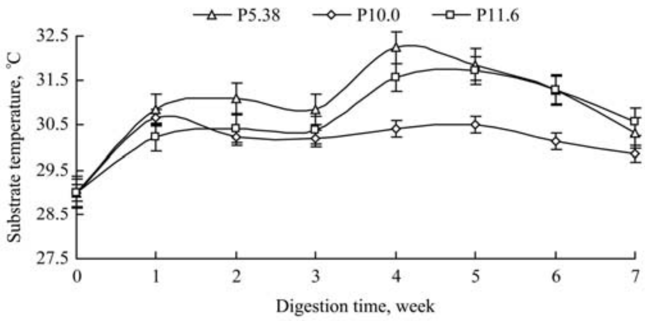
3.1 Substrate temperature

The average substrate temperature during digestion did not differ ($p > 0.05$) across the *MT* and *SA* (Table 3). The daily temperature (*DT*) of substrates ranged between 28.7°C and 34.7°C during digestion. The agitation of the digesters once daily would have enhanced uniformity of substrate temperatures. The *DT* values were averaged weekly and presented in Figure 1. The average temperatures exhibited similar trends in all the treatments by rising from an initial value of 29.4°C to 30.2°C-30.9°C (PM), 30.2°C-32.3°C (CD) and 29.0°C-31.8°C (SM) within the first week of the experiment. The PM treatments attained peak temperatures during weeks 4 and 5 before dropping gradually to 29.9°C-30.6°C by week 7. The CD treatments had the highest temperatures during the week 1 and fluctuated slightly (±1.25°C) before dropping to final values between 29.5°C and 31.0°C. The SM treatments showed a different pattern with S10.0 having significantly lower temperatures and S5.38 and S11.6 having same trend and close temperature values. No significant ($p > 0.05$) correlation was established between substrate temperature and other parameters measured.

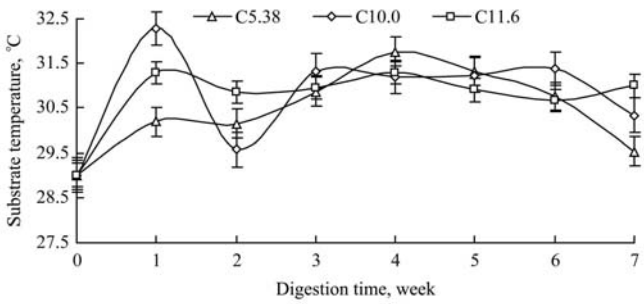
Table 3 Duncan's multiple range tests showing the means separation

Parameter	*MT*			*SA*, dm^2		
	PM	CD	SM	5.38	10.0	11.6
Temperature, °C	30.8^a	31.0^a	30.1^a	30.8^a	30.0^a	31.1^a
pH	6.32^a	6.34^a	6.27^a	6.28^a	6.33^a	6.33^a
Biogas, L kg^{-1} VS fed day^{-1}	1.00^a	0.11^c	0.59^b	0.27^b	0.68^a	0.74^a

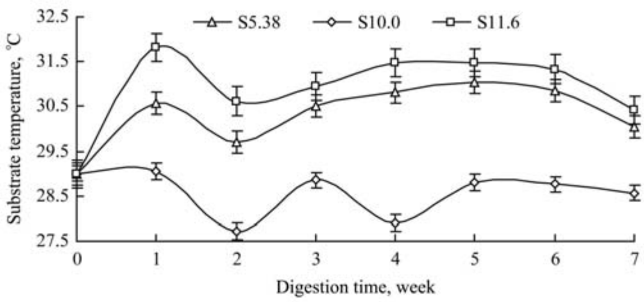
Note: Superscripts with the same letter are not statistically different at $p \le 0.05$ significance level.



a. PM



b. CD



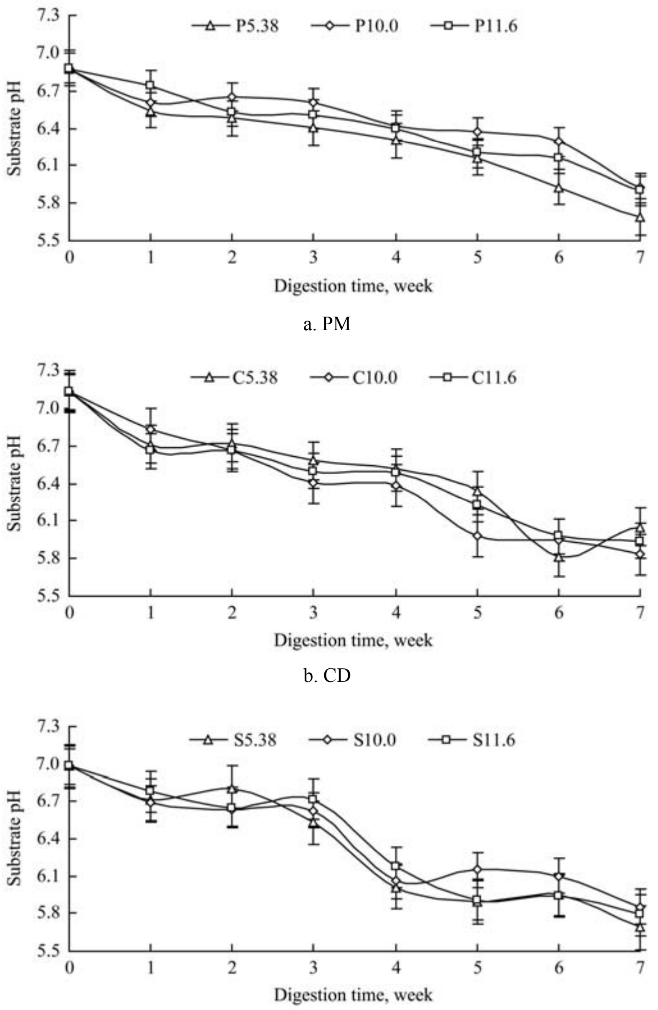
c. SM

Notes: Error bars show standard errors of means ($n=3$).

Figure 1 Variation of substrate temperature with digestion time

3.2 Substrate pH

The average pH values of the substrates during digestion were not significantly different ($p > 0.05$) in all the treatments (Table 3). The initial pH of the manures were within the range (6.8-7.2) considered ideal for anaerobic digestion (Ward et al., 2008). Starting from initial values of 6.88, 7.13 and 6.98, the pH dropped gradually with digestion time in all the treatments to final values between 5.69-5.92, 5.83-5.94 and 5.69-5.85 in PM, CD and SM substrates, respectively (Figure 2). The drops implied the production of volatile fatty acids as the easily digestible fraction of the substrates was being hydrolyzed (Comino et al., 2009). The rate of pH drop per week ranged from 0.11 to 0.15 (R^2 from 0.88 to 0.98) in PM substrate, 0.16 to 0.19 (R^2 from 0.88 to 0.98) in CD substrate and 0.15 to 0.19 (R^2 from 0.90 to 0.92) in SM substrate. The final pH values (5.69-5.94) were below the range of 6.0-8.5 recommended for organic matter compatibility with most plants (Lasaridi et al., 2006). However, the digestate could be left to cure before application to plants.



a. PM

b. CD

c. SM

Notes: Error bars show standard errors of means ($n=3$).

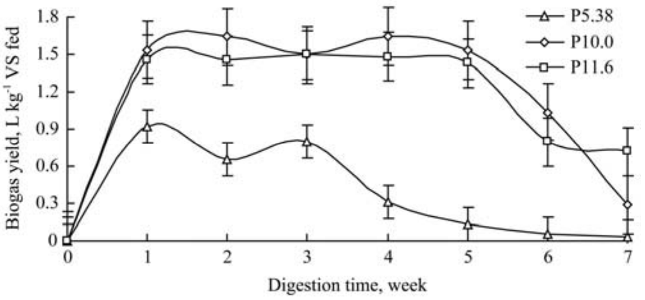
Figure 2 Variation of substrate pH with digestion time

3.3 Biogas yield

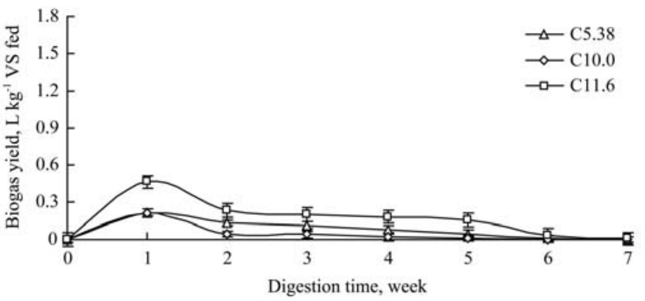
The results of the Duncan's multiple range tests (Table 3) showed that PM produced the highest quantity of biogas while CD produced the least. This finding was in conformity with previous anaerobic digestion studies (Adewumi, 1995; Itodo and Awulu, 1999; Ojolo et al., 2007) and was attributed to high biodigestibility of PM (Odeyemi and Adewumi, 1982). SA of 11.6 dm^2 produced the highest quantity of biogas while *SA* of 5.38 dm^2 produced the least (Table 3). This implied that *BY* increased with digester *SA*. The effects of *SA* showed that 10.0 and 11.6 dm^2 produced the same quantity (p>0.05) of biogas (Table 3). The non-significance in their yield may be related to the closeness in the *SA*. *SA* of 10.0 dm^2 is 86.2% of 11.6 dm^2 while that of 5.38 dm^2 is 46.4% of 11.6 dm^2. Biogas production started within 24 h in all the treatments. The daily biogas production of each treatment fluctuated repeatedly and peaked at different days during digestion. The differences in peak periods were attributed to the differences in organic matter content and the degree of biodigestibility of the manures (Odeyemi and Adewumi, 1982). PM and SM substrates produced biogas throughout the digestion period but CD substrates had productions stopped on the 42nd, 39th and 45th day in C5.38, C10.0 and C11.6, respectively. The stoppage of production suggested completion of the digestion process or process inhibition due to volatile fatty acid accumulation (Bouallagui et al., 2001). The weekly production clearly showed that P10.0 and P11.6 followed closely throughout the digestion time (Figure 3a). This pattern was also exhibited by the S10.0 and S11.6 (Figure 3c). The peak productions for the PM substrates were recorded during weeks 1 and 4 for P5.38, and P10.0 and P11.6, respectively. However, for the CD and SM substrates, the peak productions were during week 1 (Figure 3b and 3c).

The cumulative yield showed that *SA* of 5.38 dm^2 produced the least quantity of biogas (Table 4). Although CD substrate produced the least volume of biogas during digestion, by week 2 the substrate had produced 55%-77% of the total biogas while PM and SM substrates produced 33%-55% and 35%-41%, respectively. The early high productions may be attributed to the initial

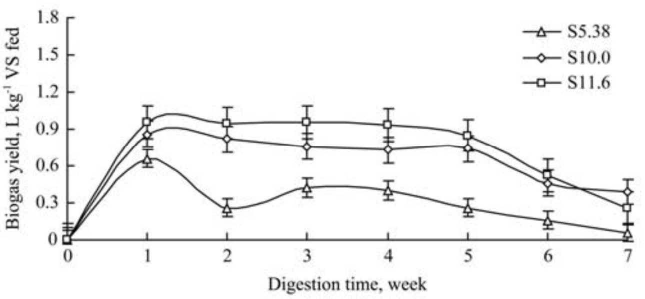
C: N ratio of the CD which was within the recommended range of 20:1-30:1 for effective biodegradation.



a. PM



b. CD



c. SM

Notes: Error bars show standard errors of means ($n = 3$).

Figure 3 Variation of weekly biogas yield during digestion for different substrates

Table 4 Cumulative biogas production (L kg^{-1} VS fed)

MT	*SA*, dm^2			*p*-value
	5.38 (0.7)	10.0 (1.8)	11.6 (2.3)	
PM	20.3^a	65.0^b	61.6^b	0.003
CD	4.16^c	2.37^b	8.92^a	0.001
SW	15.8^a	33.4^b	38.2^b	0.026

Note: Superscripts with the same letter are not statistically different at $p \le 0.05$. Values within parentheses are *DD/SH ratios*.

The significant ($p \le 0.05$) correlation established between substrate pH and *BY* showed that the former may have affected the latter. The drops in the substrates pH below 6.6 (observed between weeks 2 and 3) may have greatly reduced the growth rate of methanogens (Mosey and Fernandes, 1989).

The regression equations derived from the *DD/SH ratio* and *BY* data are presented in Table 5. The predicted curves (Figure 4) showed that only the polynomial model gave a practicable scenario as logarithmic, power and linear models gave exponential increase in *BY* as the *DD/SH ratio* increased with substrate depth tending to zero. In a digester, biogas, scum, supernatant, digested slurry and inorganic solids layers are formed during digestion. It would therefore be impossible to keep having increase in biogas production with these layers assuming infinitesimal values. The polynomial model presented an ideal situation with a dome-shaped curve (Figure 4), predicted that the minimum *DD/SH ratio* at which biogas production would commence is ≈ 0.3 while at ratio ≈ 2.5, maximum production would be recorded (Figure 4). Also, biogas production would cease when *DD/SH ratio* is greater than 4.6.

Table 5 Regression equations showing the relationship between *DD/SH ratio* and *BY*

Model	Equation	R^2
Linear	$y = 0.3183x + 0.0586$	0.970
Logarithmic	$y = 0.4211 \ln(x) - 0.4159$	0.995
Polynomial	$y = -0.3183x^2 + 0.7777x - 0.2043$	1.0
Power	$y = 0.3729x^{0.9113}$	0.988

Note: *y*: *BY*, *x*: *DD/SH ratio*.

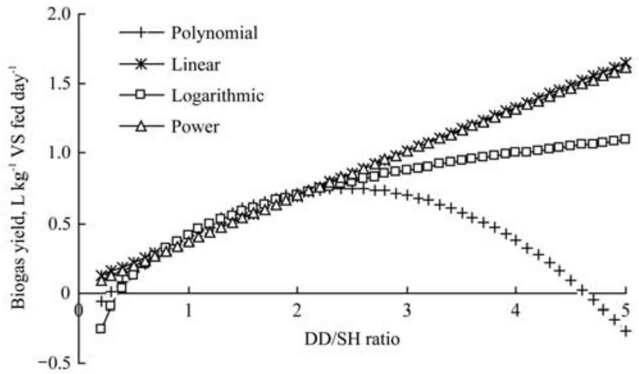


Figure 4 Regression curves relating *DD/SH ratio* and *BY*. Biogas production commenced at *DD/SH ratio* ≈ 0.3, peaked at ≈ 2.5 and ceased at ≈ 4.6

4 Conclusions

The results from the study indicated that *MT* and digester *SA* significantly affected biogas production. PM was found to be the best in terms of *BY*. It was observed that *BY* increased as the *SA* increased within the three *SA*s tested. Neither the digester *SA* nor *MT* significantly affected substrate temperature or pH. The results of the regression analysis showed that a polynomial model presented an ideal situation and best described the relationship between *DD/SH ratio* and *BY* through a dome-shaped curve, indicating *DD/SH ratios* at which biogas production would commence, peak and cease.

Nomenclature

Symbol	Definition
P5.38, P10.0 and P11.6	poultry manure substrate in digesters with 5.38 dm^2, 10.0 dm^2 and 11.6 dm^2 surface areas, respectively
C5.38, C10.0 and C11.6	cow dung substrate in digesters with 5.38 dm^2, 10.0 dm^2 and 11.6 dm^2 surface areas, respectively
S5.38, S10.0 and S11.6	swine manure substrate in digesters with 5.38 dm^2, 10.0 dm^2 and 11.6 dm^2 surface areas, respectively

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